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ScienceDirect

Energy Procedia 78 (2015) 97 – 102

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Evaluation of influence of header design on water flow characteristics in window cavity with CFD

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Abstract

Water flow window is a multi-glazing system with a flowing water layer in the cavity. The water flows in a closed loop which is connected to a double-pipe heat exchanger. Two headers with evenly distributed openings are located at the top and bottom ends of the window cavity. Water flow and temperature distribution in the cavity are studied with different header designs in this numerical study. It is found that the change in opening size or interval will affect the local distribution of temperature and flow velocity around the headers. But their effect on the overall system performance is insignificant.

Keywords: Water flow window; header design; CFD; interval and opening size

1. Introduction

The novel idea of water flow window was first proposed by Chow et al. [1] in year 2010. This window system is consisted of two main parts: the glazed area and the double-pipe heat exchanger sealed in the window frame. The first part is consisted of two glazing panes and flowing water stream in between. The flow is buoyance driven, in a closed loop connecting the two parts. The physical arrangement and energy flow path of the system is shown in Fig. 1. Since the thermal extraction capacity of water is much higher than air, this system contributes to building energy saving from two aspects: the reduction in room cooling load (for cooling dominated area) and the useful water heat gain. The annual reduction in room heat gain of a double absorptive-glazing water flow window system is 32% and

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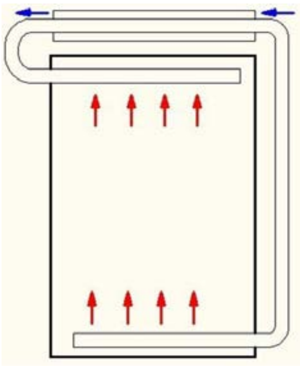
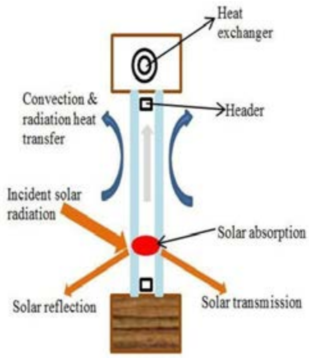
doi:10.1016/j.egypro.2015.11.121

52% respectively as compared to traditional double and single glazing system based on the application in a health club in Hong Kong [2]. The system performance is influenced by the solar radiation condition and the water flow circuitry, and it also varies with seasons [3]. Experimental study was conducted in Hong Kong with the window dimension of 2.0m (H) × 0.8m (W), and a water layer of 30mm. Based on the experiment results, the adoption of the water layer has almost no influence on the visible transmittance as compared to the traditional IGU unit, and the overall performance is attractive with an estimated economic payback period within 5 years [4].



(a)



(b)

Fig. 1. Water flow window: (a) front view showing the water circuit; (b) Side view indicating the energy flow paths.

As a matter of fact, the system design can be further improved. All factors, including the dimensions of window, heat exchanger and window cavity, and also the design of header could alter the flow characteristics and the system performance. This article reports on the evaluation of header design, and in particular the influence of the distribution and size of openings.

2. Research methodology

The evaluation is based on an optimal design of window with height of 1.2m and width of 0.8m. The water layer thickness is 20mm, and the diameters of the outer and inner pipes of the heat exchanger are 30mm and 20mm respectively. The computation analysis was through the GAMBIT and FLUENT software package. Each header is 800mm long. By leaving a 40mm section at both ends, the effective length for water path is 720mm. Openings are distributed evenly on the headers. Intervals of 20mm and 30mm and opening sizes of 1mm, 2mm and 3mm given in Table 1 are evaluated case by case. A header with interval of 30mm and opening diameter of 1mm is shown in Fig. 2 as an illustrating example.

Table 1. Test cases of header design

Interval(mm)	**Opening diameter (mm)**		
20.0	1.0	2.0	3.0
30.0	1.0	2.0	3.0

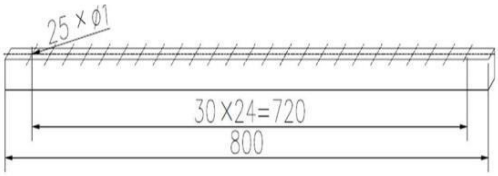


Fig. 2. Example of header with 30m interval and 1mm diameter opening

A three dimensional CFD model was built in GAMBIT, based on the above physical dimensions in the flow domain. The header is of cross-section 14mm (W) by 27mm (H). For the openings on each header, mesh structure of triangular element was adopted and Tet/Hybrid element was used for the headers and the window cavity. Simulation was conducted by assuming that the return water flowed into and out of the window cavity from opposite sides. In this study, return water flowed into the cavity from the lower right side and flowed out of the cavity from the upper left side. The inflow water velocity of 0.021m/s was from the simulation results of a validated FORTRAN program; and the corresponding inlet water temperature was 313.88K. The outlet boundary condition was defined as outflow. The structure of the window and the headers were defined as walls, except that the openings were defined as interior to permit water flow through them. The water heat gain comes from both thermal convection and conduction via the double glazing surfaces and the absorption of solar thermal energy as well. The amount of water heat gain was first determined via the FORTRAN program, and here defined as boundary conditions. In the simulation, the heat gain of the water layer was defined by the volume heat generation rate of fluid, which was 4675.3W/m^3. The effect of window frame would be discussed in the future study and it was assumed to be adiabatic here.

In the simulation, laminar flow model was used since the flow was steadily upward at very small flow velocity. Gravitational acceleration was considered because of the buoyance driven nature. The water density was defined through a piecewise-linear function that handled the variation of density with water temperature. The pressure was discretized with standard form, and the momentum and energy equations were discretized with second order upwind method. Residuals for velocity and energy were 1×10^{-5} and 1×10^{-7} respectively.

3. Results and discussion

From our previous studies, the interval of opening was 30mm and the opening diameter was 1mm. The CFD determined outlet temperature and average velocity in the window cavity were compared with the FORTRAN simulation results, as given in Table 2. The average water velocity in the cavity was calculated as the average values at the heights of 0.5m, 0.6m and 0.7m to avoid the influence of irregular fluid flow around headers. The difference between the water outlet temperatures is 0.21K and the difference in velocity is as small as 0.00002m/s. Errors with such small values are acceptable. The good agreement in simulation results coming from the two different approaches indicates that quality results can be generated from the CFD work to evaluate the header design.

Additional CFD simulations were then conducted with the use of different intervals and opening sizes. The results of outlet temperature and average velocity in the cavity are listed in Table 3. In the table, INT refers to the interval spacing and O refers to the opening diameter (both in mm). The average velocities in the window cavity were also calculated at the heights of 0.5m, 0.6m, and 0.7m. The influence of opening size on the outlet temperature and the average water flow velocity is found very small. The difference in temperature is less than 1%, and that in velocity is only around 3%. Both differences in the outlet temperature and average velocity are small. The water average velocity in the window cavity is less than 0.0005m/s. So the effect of convection heat transfer should be extremely small. The flow close to the bottom header is influenced by the nature of water outflow from the header openings. But the maximum height of the influenced space is smaller than 0.3m from the openings of the bottom header.

Table 2. Comparison of outlet water temperature and water velocity in cavity in FORTRAN and FLUENT

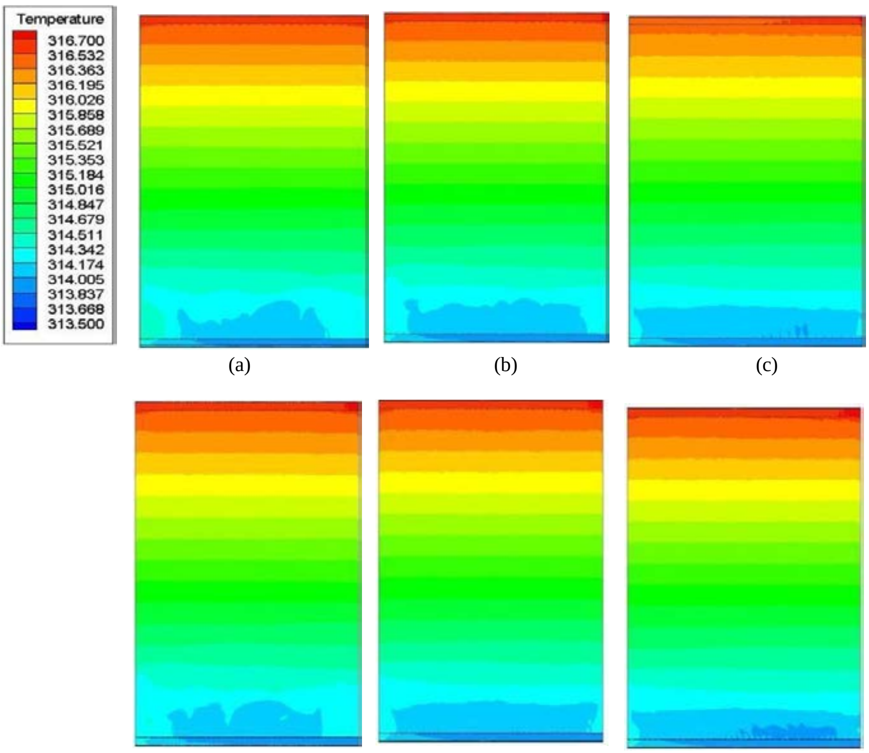
	FORTRAN	**FLUENT**
Inlet temperature (K)	313.88	313.88
Outlet temperature (K)	316.4	316.61
Velocity in window cavity (m/s)	0.00045	0.00047

Table 3. Water outlet temperature and average velocity in the window cavity

	INT30O1	**INT30O2**	**INT30O3**	**INT20O1**	**INT20O2**	**INT30O3**
Outlet temperature (K)	316.61	316.605	316.6	316.61	316.6	316.6
Average velocity (m/s)	0.00049	0.00048	0.000474	0.00048	0.00047	0.00048

Detailed distribution of velocity and temperature in the window cavity are also compared to study the influence of opening size, the variations of temperature and velocity distribution on the middle face along the Y direction are considered. The temperature distribution with different interval sizes is shown in Fig. 3. Temperature increase along the height of window can be observed clearly for all six cases. Water close to the bottom header has the lowest temperature but the area coverage is different case by case. The area filled by low temperature fluid increases with the increase of openings diameter. This is because, for the case with the largest opening diameter of 3mm, the average outflow velocity is small and thus the heat transfer will not be as good as the other cases. And also the outlet temperature for this case is slightly lower than the other cases though the difference is not evident.

To further study the water temperature variation along the window height, the results of average water temperature in the window cavity at heights of 0.1m and 1.1m, and also the corresponding temperature increase are listed in Table 4. The average temperature at the height of 0.1m of the case with 3mm opening is the smallest among the three cases. From Fig. 3, it can be seen that this is true under both conditions of interval spacing at 20mm and 30mm. The temperature increase is larger after absorbing the same amount of energy in the window cavity. The predicted temperatures at the height of 1.1m are more or less the same in all six cases.



(d) (e) (f)

Fig. 3.Temperature distributions in window cavity: (a) 30 mm interval-1mm opening; (b) 30mm interval-2mm opening; (c) 30mm interval-3mm opening; (d) 20mm interval-1mm opening; (e) 20mm interval-1mm opening; (f) 20mm interval-3mm opening

Table 4. Water temperature at height of 0.1m and 1.1m and the corresponding temperature difference

	INT30O1	INT30O2	INT30O3	INT20O1	INT20O2	INT30O3
Temperature at 0.1m (K)	314.209	314.154	314.1	314.186	314.11	314.08
Temperature at 1.1m (K)	316.386	316.382	316.38	316.387	316.385	316.383
Temperature difference (K)	2.177	2.228	2.28	2.201	2.275	2.303

The velocity distributions are shown in Fig. 4. Similar to the temperature distribution, the velocity increase along the height of window is observable, though the average velocity in the cavity is extremely small. As expected, the water velocity at the bottom header is higher with smaller opening. The average velocities at openings of bottom header are 0.5m/s, 0.115m/s and 0.046m/s respectively for cases with 1mm, 2mm and 3mm opening diameter and 30mm interval. Those corresponding velocity values with interval of 20mm are 0.336m/s, 0.073m/s and 0.031m/s. An increase in the number of openings also contributes to a reduction in outflow velocity. Low velocity has negative effect on heat transfer and thus the water temperature in the bottom window zone is also low for the case with larger opening. The average velocity at the upper window cavity of the case with 3mm opening is slightly higher than the other two cases. This should be caused by the larger temperature difference, as introduced in Table 4.

Water flow velocity increases steadily at uniform speed along the Z direction in the window cavity and the flow is mainly upward dominated. The streamlines with different openings and interval spacing of 30mm are given in Fig. 5. Water flow above 0.3m is upward flow dominated for all the three cases, and the flow is influenced by the outflow water in different degrees below this height. For the case with opening diameter of 1mm, the overall flow direction is upward though there is also horizontal flow. However, the horizontal flow plays more important role with the increase of opening size. This is especially true for the case with opening diameter of 3mm. The water flow from the height of 0.1m to the height of 0.2m is almost dominated by horizontal flow. This is because, when the opening size is small, the outflow water has higher velocity, which is upward. And this upward flow restricts the water flow along the horizontal direction. However, with an increase of opening size and a decrease of outflow velocity, the limitation on horizontal flow becomes weaker and the pressure coming from the upper fluid layer is large. Thus the flow along the X direction plays a major role around the bottom header. This is also true for the case with interval of 20mm and the variation of opening diameter from 1mm to 3mm.

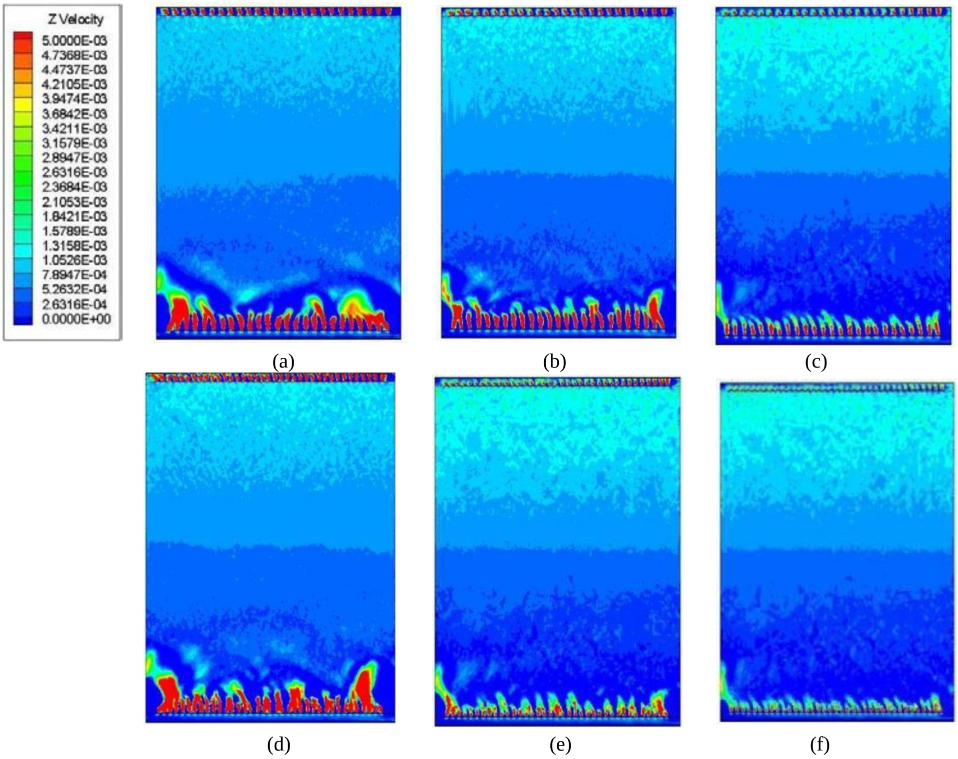
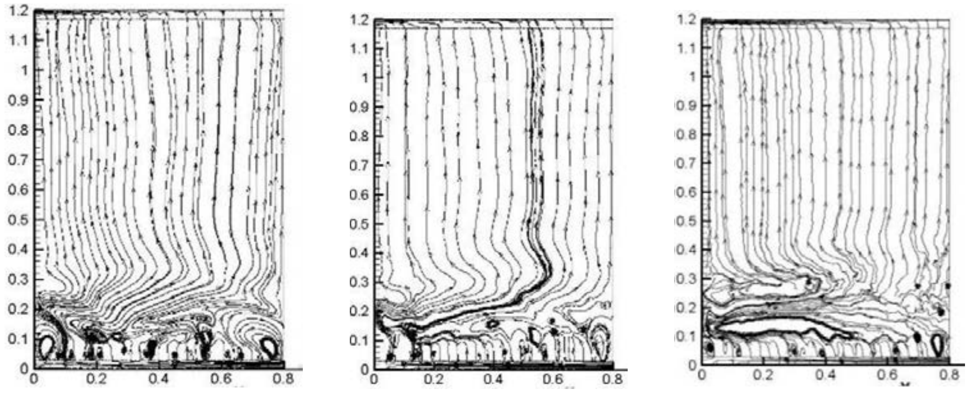


Fig. 4. Velocity distributions in window cavity : (a) 30 mm interval-1mm opening; (b) 30mm interval-2mm opening; (c) 30mm interval-3mm opening; (d) 20mm interval-1mm opening; (e) 20mm interval-1mm opening; (f) 20mm interval-3mm opening



(a) (b) (c)

Fig. 5. Streamlines of water flow with 30mm interval (a) 1mm opening; (b) 2mm opening; (c) 3mm opening

4. Conclusion

Results based on CFD simulation with 20mm and 30mm interval indicate that the variations of opening diameter have effects on the local temperature and velocity distribution around the bottom header; but the effects on the space far away from the bottom header are negligible. For both cases, an increase in opening size leads to a decrease in average outflow velocity at the openings of the bottom header, and also a lower water temperature in the space around the bottom header. The velocity increase is more evident with larger opening size because of the high temperature increase of fluid in the window cavity though the velocity is small in magnitude. Flow in the window cavity is mainly upward dominated except for the space close to the bottom header, which is partly horizontal flow dominated. The influence on the outlet temperature is negligibly small, and thus the overall system performance will be more or less at the same level.

Acknowledgement

The above work was supported by the Research Grants Council of Hong Kong (Project no. 7004030).

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